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RESEARCH ARTICLE

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The presence of an obstacle influences the stepping response during induced trips and surrogate tasks

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Abstract Falling is a frequent cause of serious injury in older adults and trips are a dominant cause of falls in this rapidly growing population. Although there are few laboratory protocols that induce actual trips, there are many protocols that utilize surrogate tasks. These surrogate tasks, which are time-critical but do not involve an obstacle, appear to share a number of biomechanical characteristics with stepping responses following a trip. However, although rapid and safe negotiation of the obstacle and restoration of dynamic equilibrium are common requisites for success, we expected that stepping response kinematics during a successful recovery from a trip over a previously unseen obstacle would be substantially different than those of surrogate tasks without an obstacle. Unexpected trips were induced in 13 older men and women by an obstacle, the presence of which the subjects were previously unaware. Selected kinematics of the leading and trailing limb stepping responses during recovery from the induced trip were compared to those of two surrogate tasks that did not involve an obstacle. Multivariate analysis of variance (MANOVA) revealed that step height, step length, peak horizontal velocity, and peak vertical velocity of the leading and trailing limbs were significantly different during recovery from the induced trip compared to the surrogate tasks. These between-task performance differences may limit the extent to which performance of the surrogate tasks accurately and precisely reflect the potential to recover dynamic equilibrium following a trip. Therefore, these findings may be applicable in the design of new or modification of existing interventions to reduce falls in older adults.

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Introduction

Fall-related injuries, a large percentage of which result from trips, and even the threat of fall-related injuries, can exert a considerable effect on the quality of life of older adults. For older adults, a particularly devastating fall-related injury is hip fracture. Up to 47% of fall-related hip fractures occur as a result of a trip (Cumming and Klineberg 1994; Nyberg et al. 1996; Norton et al. 1997). However, distal radius fractures are the most common type of fall-related fracture in older adults (Donaldson et al. 1990) and while not generally life threatening, these fractures are associated with significant morbidity (Madhok and Bhopal 1992). Characterizing the biomechanical requirements associated with restoration of dynamic equilibrium following a trip, as well as the relationships between the performance capabilities of older adults and performance requirements of the recovery task, are important objectives that underlie the design and validation of clinically relevant interventions to reduce the incidence of falls and, in doing so, reduce the number of fall-related injuries to older adults.

There has been a considerable amount of research directed at identifying reliable, valid, and sensitive indicators of fall risk, which is broadly dependent on the ability to restore dynamic equilibrium by stepping (Robinovitch et al. 2002). Performance on numerous voluntary and induced stepping tests has been proposed as an indicator of trip-related fall risk and as a measure of the ability to restore dynamic equilibrium following large postural disturbances (e.g., Medell and Alexander 2000; Owings et al. 2001; Wojcik et al. 2001). The extent to which these tasks serve as a surrogate for recovery from an unexpected trip during locomotion is necessarily reliant on the degree of between-task similarity in biomechanics, motor control, and environmental contexts. Greater similarity would be logically expected to increase the predictive accuracy and precision of the surrogate. Ideally, a surrogate task for the stepping responses following a trip during locomotion would be useful as a predictor of trip-related falls and would also find utility as a training modality by which older adults could acquire, retain and, if necessary, perform the required recovery strategies. Thus, it is important to characterize the extent to which the stepping response following an unexpected trip resembles the stepping responses following surrogate tasks.

Successful restoration of dynamic equilibrium by stepping is a time-critical motor skill in that performance is constrained by a reasonably brief available time. Thus, execution delays can be costly. For example, 100-ms delays in the initial motor response of older adults discriminated successful from failed stepping responses following an induced trip (Pavol et al. 2001; van den Bogert et al. 2002). Responses based on sensory feedback control are inherently slower than those based on feedforward control, which rely on an internal model, or representation of the motor task. Feedforward control allows preplanning of a stepping response to an expected perturbation, thereby circumventing the potentially deleterious processing delays inherent in feedback control (Miall and Wolpert 1996). Most surrogate tasks used to study stepping responses in the laboratory provide ample opportunity for the subject to plan for the postural disturbance. Thus, the stepping response may involve a larger feedforward control component than an unexpected postural disturbance, such as a trip.

Feedforward control has been demonstrated during locomotion-related obstacle negotiation. When approaching an obstacle, visual fixation of the obstacle increases as a function of obstacle height and proximity (Patla and Vickers 1997). If the position and shape/size of the obstacle is static, visual fixation is completed one to two steps prior to reaching the obstacle and is generally not acquired during steps over the obstacle with either the leading or trailing limb. So, once visual fixation of the obstacle has been completed, the trajectories of the leading and trailing limb over the obstacle are reliant on feedforward control.

Because foot-obstacle contact can disturb dynamic equilibrium, control of foot clearance over an obstacle typically includes a safety factor, which is marked by a foot clearance that is larger than necessary. The dynamic nature of the safety factor is consistent with expectations of an adaptive system that updates and modifies an internal model of the stepping task. For example, the safety factor increases when subjects step over obstacles perceived as fragile compared to solid (Patla et al. 1996), decreases as a function of experience with the stepping task (Erni and Dietz 2001; Hess et al. 2003), and is rapidly transferred to the contralateral, untrained limb (van Hedel et al. 2002). Notably, foot clearance over obstacles has been reasonably well investigated although the number of papers reporting foot clearance of both the leading and trailing limbs is limited (e.g., Patla et al. 1996; Krell and Patla 2002).

In the present study, we examined how older adults restore dynamic equilibrium after three types of large postural disturbances. Two surrogate recovery tasks reported in the literature were compared with recovery after an unexpected trip. Of the three tasks, since recovery from an actual trip is the most relevant in terms of day-to-day life, we considered this task the standard against which the others were compared. The initial conditions of these tasks vary and are described in the “Methods” section. However, each of the tasks possesses similar recovery requirements that are reliant on shared lower extremity motions. For example, the hip and knee flexion, which provide adequate foot-ground/obstacle clearance, is followed by rapid knee extension that positions the foot to establish a new base of support. Each task requires that control of the trunk be restored/maintained. However, a considerable between-task distinction is that the recovery after the trip requires the subject to negotiate, with both legs, an obstacle about which little information is available. The surrogate tasks do not have an obstacle and this is clearly evident to the subjects prior to task performance. Thus, the surrogate tasks provide ample time for the subject to preplan the recovery task. In contrast, the recovery from the trip, having eliminated a priori awareness of the obstacle, offers only minimal, if any, opportunity for preplanning.

We hypothesized that the stepping kinematics necessary to restore dynamic equilibrium following an induced trip would be significantly different than the stepping kinematics of two surrogate tasks that possess similar rapid execution requisites but that did not require the steps over an obstacle. In particular, we expected the foot trajectories following a trip would be associated with a significantly larger safety factor (i.e., larger clearance over the obstacle), reflecting the desire to avoid secondary and deleterious contact with an obstacle of minimally specified location, dimensions, and properties.

Methods

The thirteen older adults (six men, seven women, aged 72 ±5 years, height 1.65±0.09 m, weight 80±11 kg) included in this study were a subset taken from a larger study on locomotion and trips. The subjects were healthy and living independently in the community. The subjects underwent a medical history and physical examination prior to participation. Exclusion factors included the presence of neurological, musculoskeletal, and cardiovascular disorders and bone mineral density of the proximal femur of less than 65 g/cm^2, measured using dual energy X-ray absorptiometry (Hologic QDR 1000, Waltham, Mass., USA). This study was approved by the Institutional Review Board and all subjects provided written informed consent.

Each subject participated in three different protocols, performed on 3 separate days and in fixed order. The protocols imposed large postural disturbances that required a stepping response to avoid falling. During the experiments the participants were protected from a fall to the ground by an individually fitted instrumented safety harness.

In the first task, subjects were released from a static forward leaning position, the task objective of which was to restore equilibrium with a single step (Owings et al. 2000). The leaning position was sustained by a static rope, one end of which was connected to the removable core of a stationary electromagnet and the other of which was attached to the subject's safety harness. The subjects were positioned at the initial static lean angle with their arms folded across their chest, their feet aligned forward, shoulder width apart, and their heels on the ground. The subjects were instructed to recover their balance with a single large step when the magnet was released. In this task, it was visually obvious to the participants that there were no obstacles that would obstruct their stepping responses and each subject implicitly knew the task requirements. Because the only unknown was the time of the release the motor task could be preplanned. At least a portion of the non-stepping foot was to remain on the ground at its original location. The lean angle was increased at 5° increments, up to a maximum of 20°, until the maximum recoverable lean angle was determined. Data from the first trial at the maximum recoverable lean angle were used in the present study.

The second task used a motorized treadmill to induce a rapid forward-directed postural disturbance that required a stepping response to avoid a fall and, after recovering dynamic equilibrium, to continue walking (Owings et al. 2000). Initially the subject stood quietly on the belt of the treadmill (Series 1800, Marquette Electronics, Milwaukee, Wis., USA). A verbal warning preceded treadmill activation by up to 1 min. When activated, the treadmill accelerated to the designated velocity in approximately 150 ms, independent of the subject's weight. The instructions to the subjects were to recover their balance after the treadmill started to move and continue walking. In this task, it was visually obvious to the participants that there were no obstacles that would obstruct their stepping responses, and each subject implicitly knew the task requirements. Because the only unknown was the onset time of the perturbation the motor task could be preplanned. The initial treadmill speed was 0.90 m/s (2.0 mph) and was increased (decreased) upon successful (unsuccessful) recovery until the maximum velocity of 1.12 m/s (2.5 mph) was achieved. In the present analysis, data were analyzed from each subject's first successful recovery at a treadmill velocity of 1.12 m/s (2.5 mph). Across the 13 subjects in the present analysis this required 4.5±2.3 trials.

The final protocol involved recovery from a trip that was induced during locomotion (Pavol et al. 1999). Each subject walked at a self-selected velocity for a series of trials during which there was no threat of being tripped. Next, a series of trials was initiated for which subjects were told that they may be tripped. No information about the means by which the trip would be induced was provided. However, during these trials, a manually operated tripping rope was placed across the gait path as a decoy, the intent of which was to mislead the subjects as to the time, location, and means by which the trip was to be induced. Although foreknowledge was assumed to provide some preplanning of a motor response, the motor response to a foot being snagged by a rope would likely be different to that occurring in response to being tripped by a rigid obstacle. The trip was induced during mid- to late-swing by a pneumatically powered obstacle that was part of the laboratory floor, located about a meter beyond the decoy rope. The obstacle was not visible to the subject at any time prior to its activation. After being remotely triggered, the obstacle rose to a height of 5 cm in about 150 ms. Data from only one trip per subject were collected. All of the subjects successfully recovered after the trip and implemented a "lowering strategy" during which the tripped foot is rapidly lowered to the ground behind the obstacle and the contralateral foot is used to step over the obstacle and establish a new base of support (Eng et al. 1994).

During the three experiments, the motion of 19 passive reflective markers, used to establish a 13-segment model of the body (Owings et al. 2000), was recorded by a six-camera motion capture system (Motion Analysis, Santa Rosa, Calif., USA) operating at 60 Hz. For the present analysis the primary dependent variables were maximum step height, step length of the leading and trailing limbs (in the leaning task there was no trailing limb data), peak vertical velocity, and peak horizontal velocity of the leading and trailing feet. These variables were derived from the kinematics of the reflective markers placed bilaterally over the lateral malleoli. For comparison to the work of others (Chou and Draganich 1997; Patla et al. 1996), toe-marker trajectories were also calculated for the tripping task.

The first leg to step, in the case of the treadmill, or the first leg to cross the obstacle during the trip, was referred to as the "leading leg." The second stepping leg was referred to as the "trailing leg." Step lengths were calculated as the horizontal distance measured from toe-off to foot-strike for each leg. Step heights were determined as the maximum absolute height above the ground (or treadmill belt), measured from the markers on the lateral malleoli. (During quiet standing these markers were generally located 8–10 cm above the floor).

To address the possibility that between-task differences in stepping responses were related to between-task differences in the magnitude of the associated postural disturbances, the relationship between measures of the disturbance magnitude during the initial 300 ms of the tasks and maximum step height was determined. The peak angular acceleration of the trunk in flexion and extension during the initial 300 ms were selected as the measures of disturbance magnitude, based on our previous work that has implicated control of the trunk with falls by older adults (Grabiner et al. 1993, 1996; Pavol et al. 2001). Between-task differences were evaluated with three-way repeated measures analysis of variance (ANOVA). Multiple comparisons were made, where indicated, using

Bonferroni-adjusted paired t-tests. The strength of the relationships between the peak angular acceleration (flexion) and maximum step height (leading limb) were determined as correlation coefficients.

The characteristics of the single recovery step from the leaning task were found to be dependent on the lean angle. As a result, the initial statistical analysis was conducted using only the data from the tripping and treadmill tasks. A 2×2 (task by limb) repeated measures multivariate ANOVA was performed. The multiple dependent variables in the MANOVA were maximum step height, step length, peak vertical velocity, and peak horizontal velocity.

A secondary analysis compared the state variables of the leading leg during the trip, treadmill, and leaning protocols. As previously indicated, the maximum recoverable lean angle was significantly correlated with maximum step height, step length, and peak horizontal velocity ($r=0.65$, $P=0.016$, $r=0.91$, $P<0.001$, and $r=0.83$, $P=0.001$, respectively). Therefore, we limited the secondary analysis to a subset of seven subjects whose maximum recoverable lean angle was 10°. Since the leaning task had a single recovery step, only data for the leading leg were analyzed. A one-way multivariate ANOVA was used to examine the effect of the three recovery tasks on the four dependent variables described above. Unique comparisons made with secondary analysis data included tripping versus leaning, and treadmill versus leaning variables. The primary data set (consisting of all 13 subjects) was used to make comparisons between tripping and treadmill tasks. Post hoc multiple comparisons were performed using paired, Bonferroni-adjusted t-tests.

The measures reflecting the magnitude of the postural disturbance, peak linear and peak angular acceleration of the trunk segment center of mass were compared using separate three-way repeated measures MANOVA. Post hoc multiple comparisons were performed using paired, Bonferroni-adjusted t-tests. All analyses were conducted with SPSS 12.0.

Results

The trajectories of the leading and trailing limbs following the trip were different than those during the treadmill recovery (Fig. 1). The MANOVA revealed a significant effect of task ($P<0.001$) and revealed that the between-task differences in maximum step height, step length, and peak vertical velocity were significant ($P<0.001$). Peak horizontal velocity did not vary across tasks ($P=0.162$). The main effect of limb, that is, leading versus trailing, was also significant ($P<0.001$) and the between-limb differences in maximum step height, step length, and horizontal velocity were significant ($P=0.001$, $P<0.001$, and $P=0.012$, respectively). Peak vertical velocity did not vary between limbs ($P=0.124$). The interaction between task and limb was not significant.

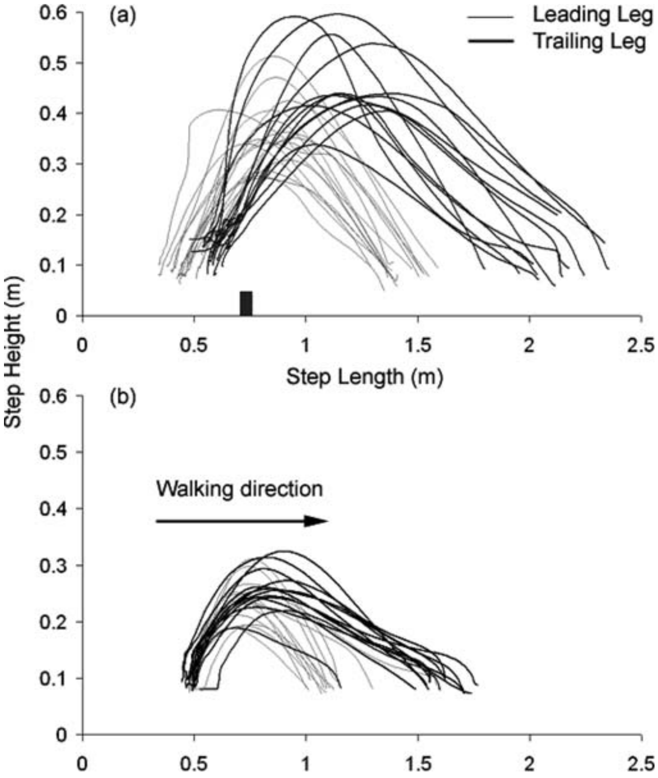

Fig. 1 Individual subject ankle trajectories in the sagittal plane from the (**a**) tripping and (**b**) treadmill protocols during which locomotion proceeds from left to right. *Light lines* indicate the leading leg trajectories, and *dark lines* indicate the trailing leg trajectories. In **a** the approximate location and size of the obstacle is marked with a *dark box*.

Maximum step height and peak vertical velocity of the leading and trailing limbs were significantly larger during recovery from the trip compared to the treadmill recovery (Table 1). The step heights of the leading and trailing legs were 51% (0.128±0.073) and 68% (0.190±0.069) m higher following the trip than following the treadmill perturbation, respectively. Similarly, peak vertical velocities for the leading and trailing legs after the trip were 58% (0.79±0.77) and 84% (0.93±0.55) m/s faster than after the treadmill perturbation. Peak vertical velocities were strongly correlated with maximum step height. For the tripping task these correlations for the leading and

Table 1 Paired t-test post hoc comparisons from the MANOVA comparing leading and trailing leg variables from tripping and treadmill tasks ($n=13$)

	Leading leg				Trailing leg			
	Trip	Treadmill	P	t (df)	Trip	Treadmill	P	t (df)
Max. height (m)	0.363	0.240	<0.001	6.1 (11)	0.434	0.258	<0.001	−9.6 (11)
Step length (m)	1.006	0.659	<0.001	−7.5 (12)	1.489	1.096	<0.001	−5.4 (11)
Peak vertical velocity (m/s)	2.161	1.37	0.003	3.7 (12)	2.022	1.098	<0.001	6.1 (12)
Peak horizontal velocity (m/s)	4.981	3.969	0.027	2.5 (11)	4.979	5.181	0.245	−1.2 (11)

trailing legs were r=0.74, P=0.006 and r=0.91, P<0.001, respectively. The peak vertical velocities of the leading and trailing legs during the treadmill task were similarly highly correlated (r=0.92, P<0.001 and r=0.80, P=0.001, respectively).

The leading step, which is crucial for restoration of dynamic equilibrium, was longer and faster during recovery from the trip than during the treadmill task (Table 1). Indeed, both the leading and trailing step lengths were longer after the trip than during the treadmill task. Leading limb peak horizontal velocity was, on average, 25% (0.95±1.29 m/s) faster during the recovery from the trip than during the treadmill task. However, peak horizontal velocities of the trailing limbs differed by only 4% and the difference did not achieve significance.

The between-limb "symmetry" of the leading and trailing limb responses was different during the recovery of the treadmill task and the trip. Whereas the difference between the maximum step heights of the leading and trailing limbs for the treadmill task were not significant (P=0.124), the maximum step height of the trailing leg was 20% (0.082±0.072 m) larger than that of the leading leg after the trip (P=0.003). The between-limb differences in peak vertical and horizontal velocity were not significant for the tripping task. However, for the treadmill task, the maximum vertical velocity of the leading leg was 25% faster (P=0.003) than that of the trailing leg and the maximum horizontal velocity of the trailing leg was 31% faster (P=0.027) compared to that of the leading leg. In contrast, for both the recovery after the trip and the treadmill task the step length of the trailing limb was 48 and 66% larger than that of the leading limb (0.45±0.241 m, P<0.001 and 0.44±0.274 m, P<0.001, respectively).

Although foot state variables during the leaning task were significantly different than those of the trip they were not significantly different than those of the treadmill task (Table 2). Because several outcome variables depended on maximum recoverable lean angle, between-task comparisons were limited to a subset of subjects, all of whom had the same maximum recoverable lean angle. MANOVA revealed significant between-task differences for leading leg step height, step length, vertical velocity, and horizontal velocity (P<0.001, P<0.001, P=0.001, and P=0.018, respectively). Compared to the leaning task, the maximum step height of the leading limb following the trip was 51% (0.111±0.043 m) higher, peak vertical velocities were 87% (1.0±0.76 m/s) faster, the step was 55% (0.33±0.108 m) longer, and peak horizontal velocity was 40% (1.4±1.36 m/s) faster. The comparisons of these variables for the treadmill and leaning tasks were not significant.

The differences between the peak angular acceleration of the trunk initially induced by the three protocols were significant (P<0.001) and suggested that the magnitude of the disturbance induced by the trip and treadmill protocols were similar to one another but different than the leaning protocol. The difference between the trip and treadmill protocols for the peak trunk flexion acceleration, about 10%, was not significant (P=0.69). However, the peak trunk flexion acceleration of the trip and the treadmill protocols were both significantly larger than that of the leaning protocol (P<0.001 and P=0.002, respectively). These differences were 181 and 208%, respectively. For the peak trunk extension acceleration, the difference between the trip and treadmill protocols, about 30%, was not significant (P=0.154). The peak trunk extension acceleration of the trip and the treadmill protocols were both significantly larger than that of the leaning protocol (P=0.001 and P<0.001, respectively). These differences were 140 and 213%, respectively.

For the three tasks, the initial angular accelerations of the trunk associated with the postural disturbances were not significantly correlated with the maximum step heights. The correlation coefficients between trunk flexion acceleration and leading limb maximum step height for the trip, treadmill, and lean were 0.142 (P=0.643), 0.354 (P=0.235) and −0.372 (P=0.211), respectively.

Discussion

The results demonstrate potentially important differences between recovery from an induced trip and recovery from two other large postural disturbances that require rapid and vigorous stepping responses. In particular, the leading and trailing foot state variables during recovery from an induced trip were considerably, and significantly different than those during recovery from a treadmill task, which has been implied as a surrogate to study recovery from a forward-directed trip (Schillings et al. 1996, 2000; Owings et al. 2001). The maximum step heights of both the leading and trailing limbs after a trip were larger, the peak vertical velocities were larger, and the step lengths were longer than the treadmill recoveries. The horizontal velocity component of the recovery limb, critical for reestablishing a base of support, was faster during a trip than during the treadmill task. The foot trajectories during

Table 2 Paired$t$-test post hoc comparisons from MANOVA comparing leading leg variables from tripping, treadmill, and leaning tasks (n=7)

	Trip	Treadmill	Lean	P (trip vs lean)	t (df)	P (treadmill vs lean)	t (df)
Max. height (m)	0.327	0.232	0.216	<0.001	6.838 (6)	0.271	1.212 (6)
Step length (m)	0.935	0.599	0.605	<0.001	8.079 (6)	0.816	−0.243 (6)
Peak vertical velocity (m/s)	2.167	1.28	1.16	0.013	3.491 (6)	0.285	1.173 (6)
Peak horizontal velocity (m/s)	4.976	3.851	3.563	0.033	2.746 (6)	0.185	1.498 (6)

the leaning task were different from the trip, but not different from the treadmill task.

A key distinction between recovery following the trip and recovery following the treadmill and leaning tasks relates to the obstacle. Information about the obstacle is entirely absent in the tripping protocol and the obstacle itself is entirely absent in the other two protocols. Since recovery from an actual trip requires restoration of dynamic equilibrium while simultaneously negotiating a previously unseen or underestimated obstacle, comparing a trip to two commonly used surrogate activities that do not involve obstacles seems a reasonable choice to elucidate the effect of the presence of an obstacle. If the presence of an obstacle truly represents a vital element of a realistic surrogate task, many presently used surrogate tasks may be easily modified to incorporate this feature.

Although the actual onset of the disturbance was difficult for subjects to predict during the leaning and treadmill protocols, the tasks shared some unambiguous aspects of the impending postural disturbance and the subsequent recovery task. For example, with respect to the latter, during the leaning and treadmill tasks it was obvious to the participants that the floor/treadmill belt was devoid of physical objects that might obstruct the stepping responses. We believe that this aspect of the tasks likely enhances preplanning of the recovery task execution, including the specification of a smaller safety factor in terms of maximum step height. Preplanning in these situations probably involves creating or updating an internal model from which the optimal recovery strategy can evolve. This allows rapid execution of the recovery step(s) using primarily a feedforward control strategy.

In contrast, recovery from the trip involved negotiation of a previously unseen obstacle possessing relatively unknown physical dimensions. The strength of the correlation between peak vertical velocity and step height suggests that the subjects who stepped the most conservatively, that is, those subjects having the largest maximum step height (safety factor), also moved their feet the fastest in the vertical direction. The inability to preplan the recovery task, coupled with the unknown dimensions of the obstacle, is consistent with a conservative solution marked by achieving a large safety factor quickly.

Compared to previously published data, recovery from the trip was associated with more conservative (i.e., larger) obstacle clearances than visually guided obstacle negotiation. Since toe clearance was the primary variable reported by previous studies, we offer toe-marker height during trip recovery for comparison. The maximum trailing limb toe height during recovery from the trip was 0.251±0.107 m. When negotiating a similar sized (51 mm) object in an experiment during which visual guidance was possible, toe clearance was 0.141±0.048 m, for a total toe height of 0.191±0.048 m (Chou and Draganich 1997). When clearing known obstacles 4 cm high, maximum toe elevation in both leading and trailing feet averaged 0.14 ±0.015 m, but the clearance of the toe over the obstacle averaged only about 0.08±0.015 m (Patla et al. 1996). This reflects a finding of the present study apparent from Fig. 1b; maximum step height does not generally occur as the foot crosses the obstacle. In fact, with regard to tripping, the maximum ankle height of the trailing leg consistently occurred after the obstacle had been crossed.

Why are the foot trajectories following a trip different from those of either planned obstacle negotiation or other tasks requiring restoration of dynamic equilibrium? One explanation presumes the role of internal models during locomotion. Walking over a benign surface requires no special planning for foot placement, since the internal model assumes that the surface is as it appears and/or is expected, i.e., level and regular. Feedforward control can be used with good results as long as the sensory input falls within the expected range predicted by the internal model. If the surface has been visually scanned, and the motion of the foot becomes obstructed by a previously unforeseen obstacle, the altered kinematic state of the lower extremity invalidates the previously used internal model. The altered kinematic state results in a substantial difference between actual and predicted sensory feedback that subsequently requires implementation of a new, or updated performance model. The new model necessarily starts with some "fuzziness" due to the ambiguity of the available information about the obstacle. The known properties of the object include its location, relative to the body's reference frame, and the hardness of the obstacle. Other crucial object properties, such as its physical dimensions, can be characterized only by possible maximum values. For example, because the toe, but not the shin or knee, contacted the obstacle, the maximum possible height of the obstacle may be estimated to be less than the height of the knee. A maximum object length may be similarly indirectly estimated because the obstacle had not previously entered the field of vision.

Once updated, the new internal model may be used to plan and control the recovery response. However, since the model is fuzzy, a conservative approach remains a reasonable solution insofar as it will increase the likelihood of a successful step with the proviso that the step requirements do not exceed the performance capabilities of the subject. Since the height of the object is unknown, the toe clearance safety factor is increased to reduce the probability of a second impact with the obstacle. Clearly, the leading and trailing foot trajectories following a trip were higher compared to other postural disturbances (Fig. 1). And, as mentioned previously, the height of steps following a trip is considerably larger than when negotiating an expected obstacle of the same height, a task for which the internal model is considerably less fuzzy.

While the initial consequence of unplanned obstacle contact is that the obstacle must be negotiated, the second and crucial consequence is the resulting loss of dynamic equilibrium. The second consequence necessitates an appropriate stepping response to restore dynamic equilibrium. This need for foot speed in both the vertical and horizontal directions reflects disparate requirements of the recovery steps. Peak vertical velocity reflects the need to avoid the obstacle while stepping over it. Peak horizontal velocity reflects the need to establish an appropriate base of support before the anteriorly directed rotation of the body causes a fall to the ground to be unavoidable. However, although increased foot clearance is necessary to avoid another, potentially deleterious contact with the obstacle, the additional time required to raise the foot is associated with increased anteriorly directed angular rotation of the body. The significantly higher peak vertical velocities in both recovery and trailing legs observed after the trip compared to the treadmill task would appear to be a partial compensation for the increased time required for the larger foot clearance. If the vertical displacement and vertical velocity are related mostly to the obstacle avoidance, the horizontal displacement and velocity would appear to be related mostly to the restoration of dynamic equilibrium. That said, the decreased lower extremity moment of inertia resulting from larger hip and knee flexion increases the potential for horizontal foot speed. The horizontal velocity comparisons between the trip and treadmill and between the trip and leaning task approached, but did not achieve significance (P=0.027 and 0.033, respectively). However, the horizontal velocity of the leading limb foot during the recovery from the trip was more than 25.5 and 40.0% larger than that of the treadmill and lean, respectively, suggesting a trend toward an important functional difference.

The differences between the stepping responses of the trip and treadmill recoveries are, in part, explained by the concept of a fuzzy internal model. In both tasks, the step length of the trailing limb was significantly longer than that of the leading limb. The maximum step height of the trailing limb was significantly higher than that of the leading limb after the trip but not the treadmill task. Since, in the tripping experiment, the trailing leg is the one that initially made contact with the obstacle, knowledge of obstacle location relative to that foot should be accurate. However, because the body's center of gravity is anterior to the trailing foot at the time of the step, foot trajectory cannot be observed without potentially deleteriously directing vision downward and backward. Therefore, it seems reasonable for the strategy to be more conservative, one that implements a larger safety factor to avoid contact with a nearby object of unknown height.

Whether the step over the object was preplanned or unplanned, the trajectory of the trailing foot is primarily under feedforward control. Even during planned obstacle negotiation tasks, significantly larger trailing leg vertical velocities and asymmetrical (leading versus trailing) step trajectories have been reported (Patla et al. 1996). When crossing tall (26 cm) obstacles, higher step elevations for trailing limbs compared to leading limbs, and greater variability in maximum trailing limb toe height were also reported. The increased variability was, in part, attributed to the absence of visual guidance of the trailing leg.

The older adults who participated in this study fit several criteria; they were able to recover from the treadmill perturbation at the fastest speed, they recovered from a trip using a lowering strategy, and they had no missing data points (for example, due to non-visible reflective markers). This, coupled with our study inclusion criteria, meant that our subjects were relatively healthy and, in addition, had good motor control. Therefore, these subjects did not represent the population of older adults most susceptible to falls. However, the focus of this study was not to directly address fall-related issues and, as a result, the sample is not considered a limitation. A possible limitation was our subjecting each older adult to the tripping protocol only once. This design was based on the assumption that a subject could effectively be surprised by the obstacle only once. Subsequent trips would necessarily involve an updated internal model and would be expected to be associated with different foot trajectories, most notably affecting step height and velocity.

The fixed order in which the protocols were administered is a limitation of the experimental design in that it is not possible to disregard the possible influence of experience with the leaning and treadmill protocols on the subsequent recovery from the trip. Within-session experience with the recovery tasks, marked by progression of initial lean angles and progression of treadmill speeds, was likely used to update the internal model and thus enhance performance of those tasks. Indeed, with respect to the treadmill protocol, recovery biomechanics of older adults are significantly improved after a single trial (Owings et al. 2001). However, within the experimental design of the present work, it is not possible to determine the extent to which previous experience with the leaning and treadmill protocols may have influenced the stepping responses after the trip. This may be important information to acquire because it could contribute to the design/redesign of protocols intended to assess fall risk and/or serve as interventions to reduce fall risk.

The morbidity and mortality associated with fall-related lower and upper extremity fractures, the surprisingly serious impairment and disability that can arise secondary to wrist fractures (Young and Rayan 2000), and the high annual incidence of each of these injuries add to the urgency and importance of uncovering how fall risk can be diminished in older adults. We believe that it would be possible to train older adults to have a higher success rate at restoring dynamic equilibrium during certain tasks. Clearly, if the number of falls were reduced the number of fall-related injuries would be similarly reduced. If task-specific training is a plausible approach to reducing the incidence of falls and fall-related injuries, then the extent to which the training task resembles the actual task is a key design consideration.

The results of the present study revealed the presence of important differences between the surrogate tasks for forward-directed trips examined here and actual trips. These differences do not appear to be related to the differences in the initial biomechanical effects of the postural disturbance, at least as measured by trunk angular acceleration. For example, the stepping responses of the tripping and treadmill protocols were considerably and statistically significantly different whereas the differences between the initial trunk flexion acceleration induced by the postural disturbances were not significant. Further, these important differences appear to be related to the presence of an obstacle. Given these findings, it may be possible to design a surrogate task that elicits a stepping response more similar to that associated with an actual trip. Such a task might improve the accuracy and precision of estimating fall risk and also be of value in providing task-specific training to older adults with the focus on successful restoration of dynamic equilibrium following a real trip.

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